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# Under-Body Blast Mitigation: Stand-Alone Seat Safety Activation System

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## ABSTRACT

This work is based on a current project funded by the United States Army Small Business Innovation Research (SBIR) Program and is being conducted with the Tank Automotive Research, Development and Engineering Center (TARDEC) Ground Systems Survivability (GSS) Team and Paradigm Research and Engineering. The focus of this project is to develop an advanced and novel sensing and activation strategy for Pyrotechnic Restraint Systems, Air Bags and other systems that may require activation. The overriding technical challenge is to activate these systems to effectively protect the Soldier during blast events in addition to Crash, Rollover and Other Injury Causing events. These activations of Pyrotechnic systems must occur in fractions of milliseconds as compared to typical automotive crashes. By investigating systems outside of typical accelerometer based applications and activations, the potential exists to exploit systems that require little power, are self-contained and provide the required output for the desired result. As such Constant-Flux Magnetostrictive Sensors shall be evaluated in a self-contained environment to provide the output during these events. By activating the Pyrotechnic Restraint Systems and Air Bag Systems early in Blast Events, the systems can Restrain the Occupant and provide flail protection from surfaces within the vehicle. As the system is developed various test scenarios will be introduced to activate these systems and design a robust sensing and activating strategy.

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## INTRODUCTION

The challenge of protecting occupants during an underbody blast is being able to sense and activate systems (such as pyrotechnic Restraints, Airbags or other protection systems) to mitigate injury to the occupant during the onset of the event. Injuries may occur as soon as 2.5 ms, therefore an activation strategy regarding pyrotechnic systems would have to occur before 1 ms in order for the system to receive the input, process the input and finally activate any and all of the pyrotechnic systems (or other protection systems). As the U.S Military evaluates various protection systems for future and current vehicle platforms the consideration of pyrotechnic systems (Pyrotechnic Restraints, Air Bags and other Pyrotechnic activated systems) will be closely considered, tested and evaluated.

Currently many U.S Military vehicle platforms utilize energy absorbing seats and energy absorbing floor mats / floor designs. These systems allow for energy to be absorbed and/or redirected from the occupant during the onset of a blast. As the seat begins stroking, it would be beneficial to activate the proper pyrotechnic system. Focusing on the Pyrotechnic Restraint system, in particular, the elimination of slack from the Restraint System would couple the occupant to the seat during the remaining duration of the blast event (Peak Height and Slam Down). Occupant flail and out of position movement, which would contribute to lower injuries to both the occupant and surrounding occupants, could be minimized.

The circuitry the pyrotechnic system is connected to would have time to activate on the onset of the blast event and initiate the pyrotechnic Restraint System at the defined time of full or optimal stroke levels.

If Military vehicle applications included a false floor, stroking seats, restraint systems and air bags (all of which were equipped with pyrotechnic devices or some sort of initiation device), essentially these systems would aid in the prevention of injuries or death. The challenge with activation systems is to take a signal input, process it and finally initiate these systems. In the chain of system activation any and all incoming data requires proper signal processing which adds complexity and time into the overall activation of any system. As a design goal typical signal processing and acceleration collection devices

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should strive to eliminate any (if not all) additional steps from sensing to activation. Aside from diagnostic support for system health and human interface, any and all circuitry with limited complexity, weight and cost is ideal for applications within Military vehicles. From Blast to Rest (Rest in terms of post slam down in an Underbody blast), the initial 3 ms will dictate if the occupant survives the event to which he/she has been subjected to. Thus activation of these systems within the microsecond range provides an opportunity for reduced injuries and death (respectively). The continuation of sensor development of this scale shall still prove crucial should Military vehicles begin to mirror automotive energy absorbing capabilities. In addition, it is crucial that sensors be able to detect initial, secondary, tertiary, quaternary, etc. events as experienced with multiple event / complex attack scenarios allowing for addition safety system activation as necessary.

Typical sensing systems utilized in the automotive field are not sufficient for Military use. Military vehicles require the additional ability to sense and send the activation signal during an Underbody Blast to the proper system in a fraction of the time as compared to a typical automotive application. In an Underbody Blast the injuries to the occupants happen within the first few milliseconds, as compared to that of a frontal crash where the first few milliseconds effects are experienced by the crushing structure of the vehicle and not yet completely transferred into the occupant. The rigid nature of Military vehicle Underbody structures allows transmission of energy to the occupant causing injuries and death. The potential for utilizing a sensor that can activate a variety of systems which prevent or reduce injuries is an investment that the U.S Army is actively pursuing.

## CURRENT TECHNOLOGY

Currently the United States ARMY does not possess a sensor system which can effectively activate passive safety systems (such as air bags and pyrotechnic restraints) to provide protection to the Soldier during underbody blast events. As such the ARMY has not integrated pyrotechnic safety systems that would provide protection in Blast, Crash, Rollovers and other injury causing events. Integration of sensors commonly found in automotive applications would not be suitable for Military vehicles, due to the fact that peak accelerations occurring in underbody blast events are larger in magnitude and occur within a shorter time span than in an automotive crash or impact event.

Comparison of frontal automotive crash and underbody blast event presented by Thyagarajan (TARDEC) [1] is shown in Table 1.

Typical automotive crash events have peak accelerations of 25 to 50 g in a time duration of 70 to 120 milliseconds (ms) as compared to underbody blast events that have peak accelerations of 100 to 400 g in a time duration of 3 to 30 ms. Further, experimental data reported by Bernstein (USAARL) and Tegtmeyer (ARL) [2] indicates a magnitude of higher floor accelerations, as high as 6000 g, within the first 1.5 ms of blast event.

Table 1. Comparison [1] of Automotive Crash and Underbody Blast.

| Event | Typical Peak Accelerations (g) | Typical Time Duration (ms) |
|---|---|---|
| Frontal Automotive Crash (30 mph) | 25 to 50 | 70 to 120 |
| **Underbody Blast** | **100 to 400** | **3 to 30** |

During the short time duration of a blast event, the Soldier experiences high accelerative loads in which injuries and deaths occur. Utilization of the standard Automotive type sensors could potentially help in mitigating injuries during Crash and Rollover events, however Blast events encountered on the battle field are more prevalent and the leading event of injuries and death. This effort will focus on designing, manufacturing and validating a sensor system that is self-contained, powered by an internal source and connected to the vehicle to provide diagnostic support and internal source charging in addition to providing the required reactionary time to activate passive safety devices. The sensor would be mounted at each seat location and would activate the necessary passive safety devices such as air bags and pyrotechnic restraint systems for that seat system in the time span of 0.5 ms from the detection of the event to the deployment of the passive safety device. For reference purposes, in an automotive crash event, the passive safety device is activated 10 ms or later depending on the event.

Sensors, such as accelerometers, strain gages and others are fast enough to detect the blast and are commercially available. However, they are too delicate to survive in a blast event and difficult to manufacture. They require external power supply and extensive signal conditioning, which also requires external power supply. They are very expensive. It is a challenge to address power and cost issues when commercially available accelerometers and other sensors are considered to be packaged as a self-contained blast detection sensor to deploy safety systems in an underbody blast.

Other shortcomings of accelerometers and other commercially available sensors pose greater technical challenges. Even after extensive signal conditioning, they have drift problems. Their offset voltage changes with time. Their signal is inherently very noisy due to electrical noise and surface vibrations. As pointed out by the reference [2] slides 16, 17 and 18, in addition to time delay, essential content of the signal is lost if filters such as CFC180, CFC600 or even CFC1000 are utilized. Therefore, it is a much greater challenge to develop a self-contained cost-effective sensor to accurately and consistently deploy airbags and other pyrotechnic restraint systems based on accelerometers and other commercially available sensors.

Constant-Flux Magnetostrictive Sensor technology offers feasible cost-effective solutions to the challenges posed by accelerometers and other commercially available sensors.

## STAND-ALONE SEAT SAFETY ACTIVATION SYSTEM

A Stand-Alone Seat Safety Activation System is developed. The system activates Pyrotechnic Systems (Pyrotechnic Restraints, Air Bags and other Pyrotechnic activated systems). Block diagram of the Stand-Alone Seat Safety Activation System is presented in Figure 1. This paper will focus on functionality of:

1. Blast Detection Sensor (BDS) based on constant-flux magnetostrictive sensor and
2. Decision Making Circuitry (DMC).

The Blast Detection Sensor continuously sleeps (its output is zero) until an underbody blast takes place. It wakes up and reports underbody blast and goes back to sleep.

The Decision Making Circuitry continuously monitors the output of the Blast Detection Sensor and creates 0 to 5 V triggering signal when preset activation criteria are met. In turn, the triggering signal activates the Initiator Power Circuitry which provides power to Pyrotechnic Restraints, Air Bags and other Pyrotechnic activated systems.

Experiments verified that the system is capable of providing power in less than 1 μs once the blast is detected and activation criterion are met.

The blast detection sensor was designed to detect blast based on acceleration levels, relative displacements and strain levels induced by underbody blast and experienced by seat and/or hull of the vehicle.

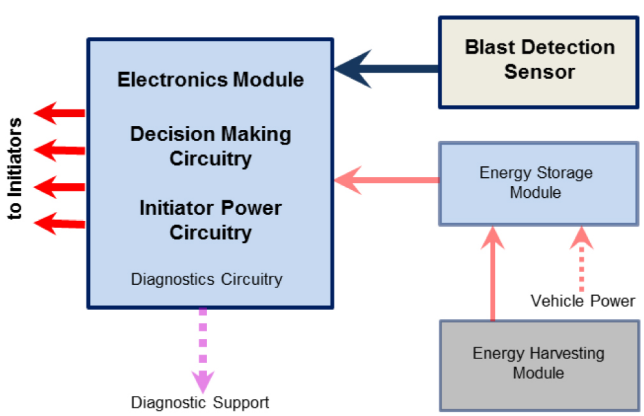


Figure 1. Block Diagram of Stand-Alone Seat Safety Activation System

The Seat Safety Activation System has its own Energy Storage Module and Energy Harvester. The Blast Detection Sensor itself does not require any electric power supply or signal conditioning. It can be installed under the seat. It can be retrofitted to existing vehicles or adapted to new vehicles.

## BLAST DETECTION SENSOR

The Blast Detection Sensor is based on a Constant-Flux Magnetostrictive sensor.

As shown in Figure 2, the structure of a generic Constant-Flux Magnetostrictive Sensor consists of a U-Core and minimum one coil. The U-Core includes a permanent magnet between two magnetically conductive (ferromagnetic) support members (legs). Each structural member of the sensor (legs and target material) is represented by a reluctance element in the magnetic circuit. The permanent magnet provides magnetomotive force (MMF) and establishes a constant flux (ϕ) in the magnetic circuit.

In the absence of any flux change, the Constant-Flux Magnetostrictive device can be characterized as a passive observer. Its output is zero (sleep mode) until a fast dynamic event such as underbody blast takes place and disturbs flux. The flux changes very rapidly when the sensor sees a dynamic event such as blast and generates a signal.

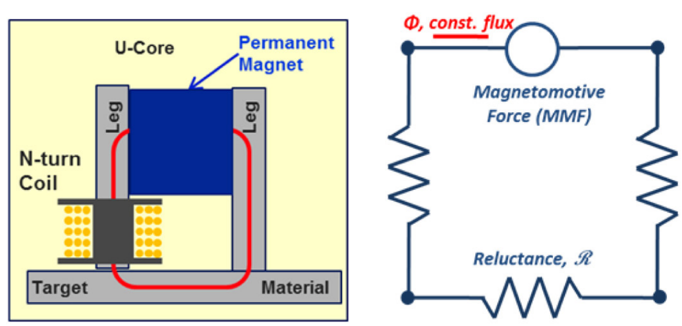


Figure 2. Constant-Flux Magnetostrictive Sensor and its Magnetic Circuit

For a coil of N-turns, output voltage V arises across terminals of the coil in accordance with Faraday's Law:

$$V = N\left|\frac{d\phi}{dt}\right| \quad (1)$$

The Faraday's Law suggests that the faster the flux changes, the higher the output voltage V or the faster the dynamic event (blast is an extremely fast event), the higher the output.

The device has a "closed magnetic circuit" if there is no air gap between structural members of the device. In a constant-flux device that forms a closed magnetic circuit, the flux change results from the inverse magnetostriction, which is the change in magnetic properties when material is subjected to changing mechanical deformation or strain.

The device has an "open magnetic circuit" if there is an air gap between structural members of the device. In a constant-flux device that forms an open magnetic circuit, the flux change is primarily due to the change in the reluctance of changing air gap resulting from a dynamic event. In constant flux devices, the air gap located at a critical point in the magnetic circuit amplifies the output of the device and provides additional design options to the engineer.

The Constant-Flux sensors can be operated in different modes. Reader is referred to the reference 3 for details.

In the presence of rapidly changing flux, properly designed and strategically located constant-flux magnetostrictive sensor's output spikes instantly. Blast Detection Sensor was designed to detect underbody blast by detecting accelerations, strains and relative displacements induced by an underbody blast.

Functionality of the seat safety activation system was tested and verified through drop tower experiments.

## TESTING OF THE SEAT SAFETY ACTIVATION SYSTEM

Repeatability and reliability of the Blast Detection Sensor (BDS) and Decision-Making Circuitry are critically important in order to activate the initiators of air bags and pyrotechnic restraint system such as airbags at the very first time the deployment criterion is met in an underbody blast event. Otherwise it would be either too late or cause false activation. Both scenarios are unacceptable.

A drop tower shown in Figures 3 and 6 experimentally simulates effects of the blast: It can generate high accelerations and impact strains similar to the ones induced by blast.

The Seat Safety Activation System and its components were tested through drop tower experiments under two different effects of the blast: Accelerations and Strains.

### *Testing of the Activation System under Impact Strains*

The Blast Detection Sensor, in this case, is sensitive to the strain changes, like traditional strain gages.

Referring to the drop tower shown in Figure 3, the drop weight freely rides on the vertical smaller diameter precision rod. Depending on the height, the Blast Detection Sensor is subjected to considerable impact strains when the weight is lifted up, released and hits the sensor.

It is assumed that the impact strains generated by this drop tower are representative of the strains experienced by, for example, the hull/floor of the vehicle as a result of an underbody blast.

The Decision Making Circuitry (DMC) is designed to accept inputs from multiple sensors. DMC allows setting of activation criterion for each sensor independently. Trigger voltage level setting represents the activation criterion and DMC is design to accommodate a wide range of trigger voltage level. The experimental results at two different levels are presented in this study. The trigger level must be set to activate the system in a timely manner so that, for example, hull or seat accelerations will not exceed certain g levels. At the same time, false activations, for example, due to road irregularities must be avoided.

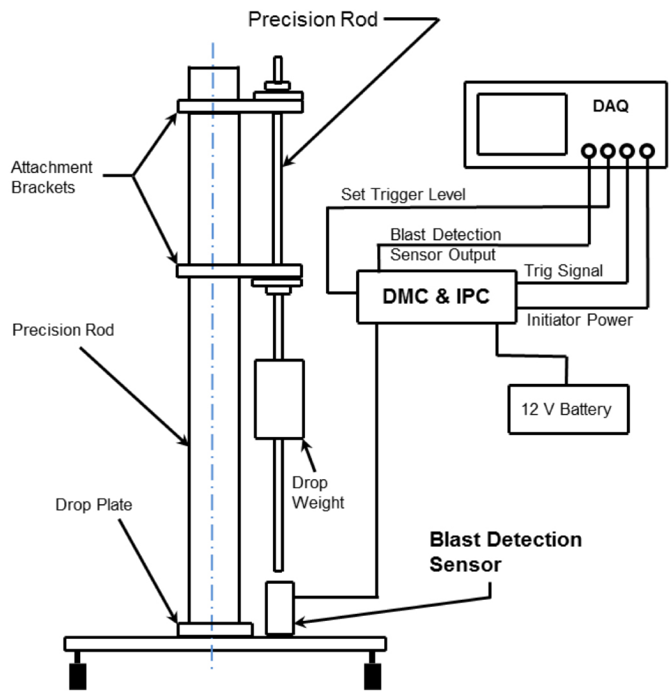


Figure 3. The Drop Tower Experimental Setup to test Seat Safety Activation System under impact strains induced by impact force.

Repeatability and accuracy of the Decision Making Circuitry (DMC) was tested quickly. The trigger level of the Decision Making Circuitry was arbitrarily set to 1.432 V which represents the activation criterion. The output of the Blast Detection Sensor, set trigger level of the Decision Making Circuitry and the Triggering Signal generated by the Decision Making Circuitry were recorded simultaneously at 2 GSa/s sampling Rate. The experiment was repeated 60 times. The Decision Making Circuitry always generated a Triggering Signal, never missed. Triggering Signal was generated when Blast Detection Sensor Output reached to 1.472 V almost all the time. The difference between set trigger level (activation criterion) and the voltage at which triggering signal was generated by DMC is less than 3% of the activation criterion. These results are pretty good especially considering resolution of the data acquisition system which is 8-bit.

After verification of functionality of the DMC, complete activation system was tested. The trigger level of the Decision Making Circuitry was kept at 1.432 V. The drop weight was lifted up and released. The output of the Blast Detection

Sensor, set trigger voltage of DMC, Triggering Signal generated by DMC and output of the Initiator Power Circuitry were recorded simultaneously at a sampling rate of 100 MSa/s. The activation system was very repeatable, functioned as expected in all experiments. Figure 4 shows plot of a typical data.

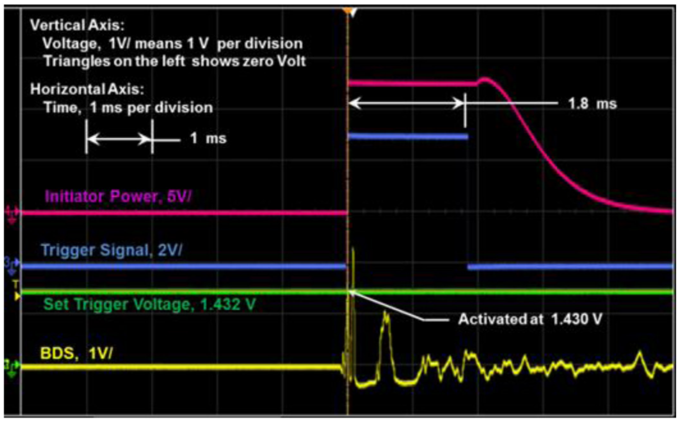


Figure 4. Testing Seat Safety Activation System under Impact Strains. Sampling Rate: 100 MSa/s.

Referring to Figure 4, the horizontal axis is time. Each division represents 1 ms. The vertical axis represents voltages. Small triangles on the far left indicate zero V or ground level for each signal. The scales are:

| | |
|---|---|
| Blast Detection Sensor (BDS), 1V/ | 1 V per Division |
| Set Trigger Voltage, 1.432 V, the same zero level as BDS, 1V/ | 1 V per Division |
| Trigger Signal, 2V/ | 2 V per Division |
| Initiator Power, 5V | 5 V per Division |

The format of the data is the same for the data presented later.

The Decision Making Circuitry generated the 0 to 5 V triggering signal when Blast Detection Sensor (BDS) output was reached to 1.430 V. Triggering Signal (TS) activated the Initiator Power Circuitry (IPC) for about 1.8 ms. The 12 V power was available for the initiator for about 2 ms. After the impact the BDS output, Trigger Signal and Initiator Power return back to zero.

The expanded (1000x) view of the same data is presented in Figure 5. In this view, the time scale (horizontal axis) is 1 μs per division. The experimental data shows that the Seat Safety Activation System is capable of activating the Pyrotechnic Systems (Pyrotechnic Restraints, Air Bags and other Pyrotechnic activated systems) in approximately 0.8 μs when activation criterion was met.

The initial oscillations of the trigger signal and initiator power will be minimized in the next generation of the Decision Making Circuitry. It is expected that the time to generate 0 to 5 V trigger signal, in other words the time to activate seat safety system, will be shortened significantly.

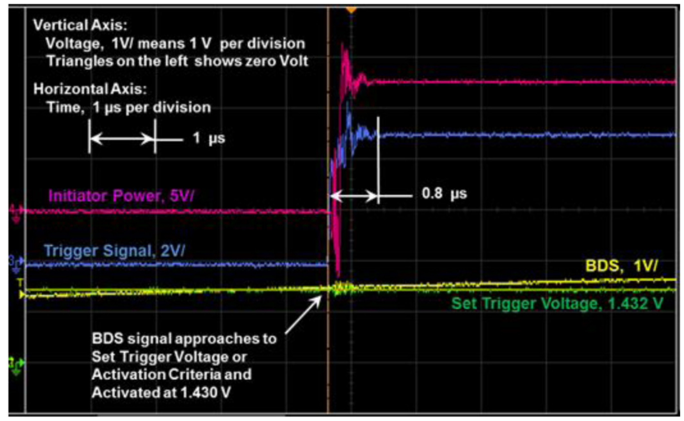


Figure 5. Testing Seat Safety Activation System under Impact Strains. Sampling Rate: 100 MSa/s. 1000x Expanded View (in horizontal direction or time) of the data presented in Figure 4.

### Testing of the Activation System under Accelerations

The Blast Detection Sensor, in this case, is sensitive to the accelerations, like traditional accelerometers.

Referring to the drop tower shown in Figure 6, the drop plate freely rides on the vertical larger diameter precision rod supported by a thick horizontal plate. When the drop plate is lifted up and released, depending on the drop height, it can generate several hundred g accelerations when it hits the heavy bottom plate and bounces back.

It is assumed that the accelerations generated by this drop plate are representative of the accelerations experienced by, for example, hull/floor of the vehicle or seat induced by an underbody blast.

The Blast Detection Sensor (BDS) and a commercial accelerometer are mounted on the top surface of the plate at a same distance from the center of the rod. This particular accelerometer's sensitivity is 50 g per division (10 g per Volt, 5 V per division). The response of the Blast Detection Sensor (BDS) was tested first. The drop plate was lifted up and released. The outputs of the Blast Detection Sensor and the commercial accelerometer was recorded simultaneously at 100 MSa/s sampling rate. A typical data plot is presented in Figure 7. The blast Detection Sensor generated a sharp clean signal reporting high accelerations.

After verifying the functionality of the Blast Detection Sensor with acceleration input, a complete activation system was tested. The set trigger level of the Decision Making Circuitry was 0.950 V. The drop plate was lifted up and released. The output of the Blast Detection Sensor, Accelerometer, Trigger

Signal generated by DMC and output of the Initiator Power Circuitry were recorded simultaneously at a sampling rate of 100 MSa/s. The activation system functioned well as expected in all experiments. Data was repeatable. Figure 8 shows plot of a typical data.

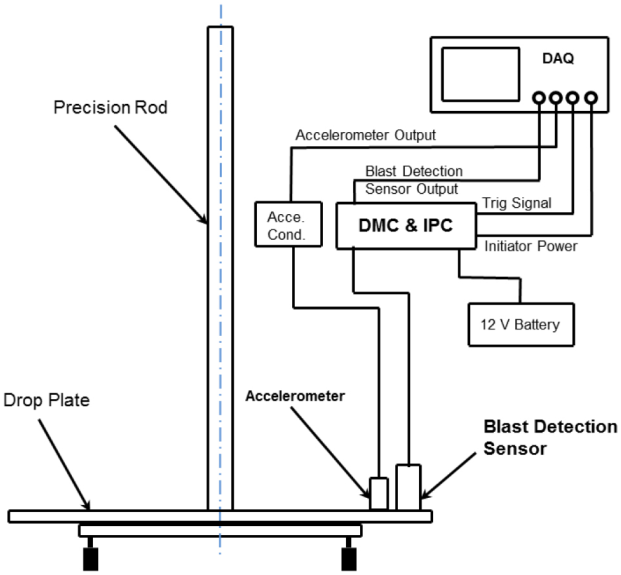


Figure 6. Drop Tower and Experimental Setup to test Seat Safety Activation System under high accelerations. Blast Detection Sensor and the Accelerometer are mounted at the same distance from the center of rod, not side-by-side as depicted in this Figure.

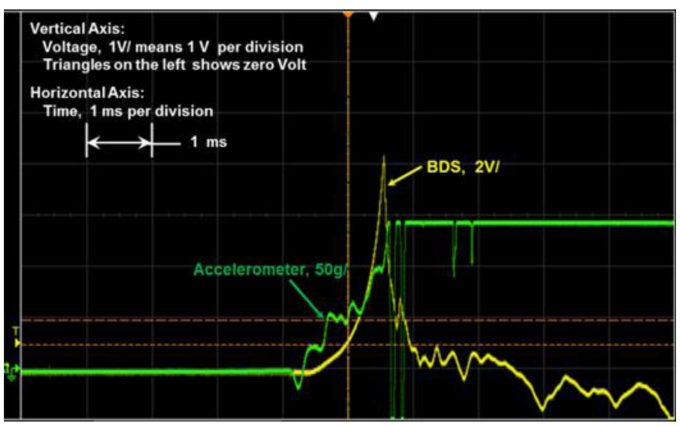


Figure 7. Testing of the Blast Detection Sensor itself under high Accelerations.

The Decision Making Circuitry generated the 0 to 5 V triggering signal when Blast Detection Sensor (BDS) output was reached to 0.935 V. The acceleration measured by the accelerometer was 43.5 g. The triggering signal was 1.8 ms long. As presented before, the triggering Signal (TS) activated the Initiator Power Circuitry (IPC) for about 1.8 ms. The 12 V power was available for the initiators for about 2 ms. After the impact the BDS output, Trigger Signal and Initiator Power return back to zero.

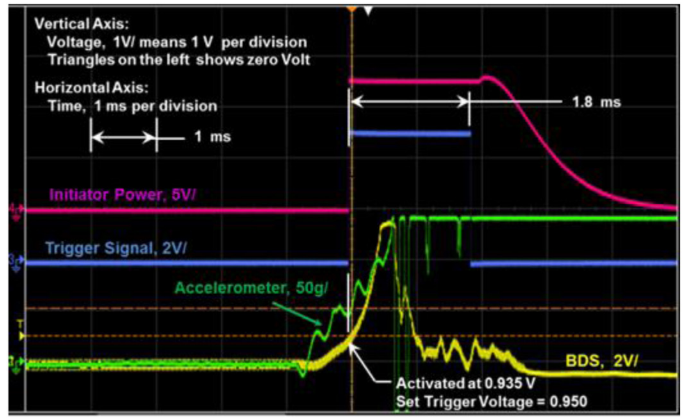


Figure 8. Testing Seat Safety Activation System under high Accelerations. Sampling Rate: 100 MSa/s.

The expanded view of the data is presented in Figure 9. In this view, the time scale (horizontal axis) is 1 μs per division. The experimental data shows that the Seat Safety Activation System activated the Pyrotechnic Systems (Pyrotechnic Restraints, Air Bags and other Pyrotechnic activated systems) in approximately 0.8 μs when activation criterion (in this experiment, happens to be 43.5 g acceleration) was met.

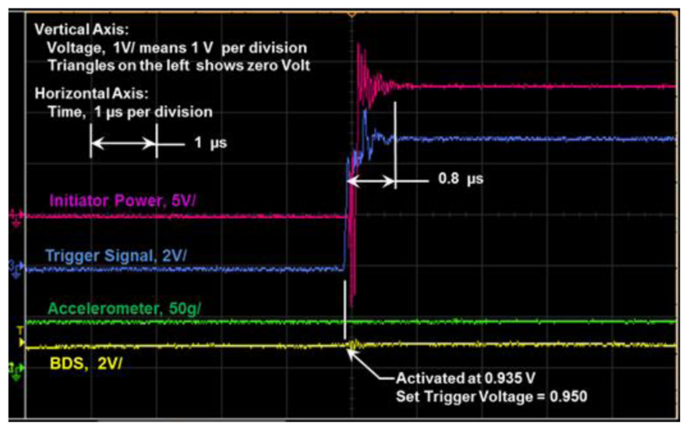


Figure 9. Testing Seat Safety Activation System under high Acceleration. Sampling Rate: 100 MSa/s. 1000x Expanded View (in horizontal direction or time) of the data presented in Figure 8.

Data presented in Figures 7 and 8 show that, the accelerometer signal saturated around 140 g. The maximum accelerations perhaps reached to 200 g.

Compared to the response of the accelerometer as shown in Figures 7 and 8, the Blast Detection Sensor's response seems to be a little slow at the beginning and catches up after accelerations exceed 50 g. However, that observation is not completely true. There are other contributing factors. Practically, it is impossible to install both the accelerometer and the Blast Detection Sensor on the same exact location. Both the accelerometer and the Blast Detection Sensor (BDS) are installed on the same centerline normal to the long dimension of the Drop Plate. The accelerometer is closer to one edge of the drop plate and the BDS is closer to the other edge. As

evidenced by Figure 10, it is possible that they could see different accelerations when the drop plate hits the bottom plate.

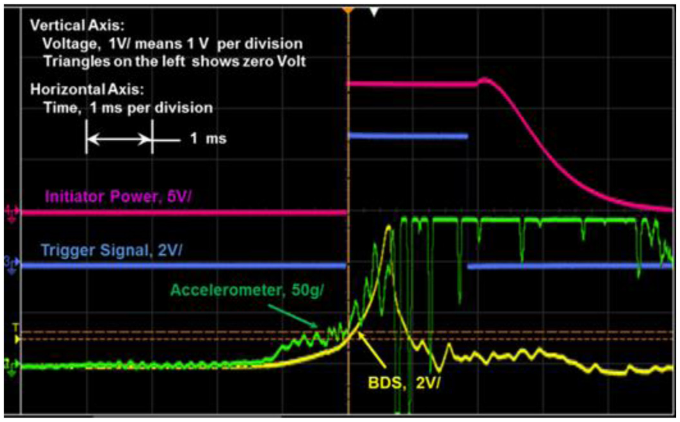


Figure 10. Testing Seat Safety System under High Accelerations. The Sampling Rate: 100 MSa/s. The test Conditions are identical to those in Figure 8 but BDS side of the Drop Plate hits first when it drops.

In the experiment presented in Figure 10, two layers of bubble-wrap were placed over the bottom plate so that Blast Detection Sensor (BDS) side of the drop plate hits first when drop plate was lifted up and released. As shown in Figure 10, BDS and Accelerometer responses are closer to each other compared to the case presented in Figure 8.

## SUMMARY AND CONCLUSIONS

A Stand-Alone Seat Safety Activation System to protect Soldiers in an underbody blast event was developed and tested. The system is capable of activating Pyrotechnic Systems such as Pyrotechnic Restraints, Air Bags and other Pyrotechnic activated systems which has some kind of initiator similar to the ones used in automotive industry.

The system consists of a Blast Detection Sensor (BDS) based on magnetostriction, a Decision Making Circuitry (DMC) and Initiator Power Circuitry (IPC). The Seat Safety Activation System has its own Energy Storage Module and Energy Harvester. The Seat Safety Activation System would fit in the space under the seat.

The Blast Detection Sensor (BDS) is sensitive to accelerations, strains and relative displacements. It detects underbody blast by monitoring accelerations, strains and relative displacements between vehicle components.

Blast Detection Sensor does not require an electrical power supply, amplification or signal conditioning. BDS has no noise or drift problems. It is rugged and cost-effective.

Currently available sensors such as accelerometers require power supply and extensive signal conditioning. They have drift problems. They are noisy. Essential content of their signal is lost if filters such as CFC180, CFC600 or even CFC1000 are utilized. They are delicate and expensive.

The Stand-Alone Seat Safety Activation System could be retrofitted to existing military and civilian vehicles or could be integrated into new vehicles. It can also be used to detect crash and all the other fast dynamic events in addition to underbody blast.

The Seat Safety Activation System was tested through drop tower experiments which experimentally simulates effects of underbody blast. Based on experimental data:

1. The Stand-Alone Seat Safety Activation System is capable of activating initiator of Pyrotechnic safety system in less than 1 μs after it detects the blast event.
2. The Decision Making Circuitry consistently detected blast and provided power for the initiators in all the tests once the blast detection criterion was met.
3. The Seat Safety Activation System works under all three effects of underbody blast: accelerations, strains and relative displacements.

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